

Herbig-Haro Objects - Tracers of the Formation of Low-mass Stars and Sub-stellar Objects

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Abstract Herbig-Haro objects (HHOs) are caused by outflows from young objects. Since the outflow relies on mass accretion from a circumstellar disk, it indicates ongoing growth. Recent results of infrared observations yielded evidence for disks around brown dwarfs. This suggests that at least a certain fraction of brown dwarfs forms like stars. Thus, young sub-stellar objects might cause HHOs as well. We present selected results of a general survey for HHOs based on DSS-II plates and CCD images taken with the Tautenburg Schmidt telescope. Numerous young objects could be identified due to their association with newly detected HHOs. In some cases the luminosity is consistent with very low-mass stars or close to sub-stellar values. This holds for L1415-IRS and a few infrared sources embedded in other dark clouds (e.g., GF9, BHR111). The question on the minimum mass for outflow activity is addressed.

Keywords ISM: clouds, individual(GF9, LDN1415, BHR111), Herbig-Haro objects, individual(HH892), jets and outflows — stars: formation, low-mass, brown dwarfs, individual(BHR111-IR, IRAS04376+5413, IRAS20503+6006)

1 Introduction

Herbig-Haro objects (Herbig (1950), Haro (1952)) are tracers of pre-main-sequence stars (Reipurth and Bally 2001). They point to the presence of young objects

while these are still deeply embedded. Recent observations of brown dwarfs (BDs) yielded evidence for accretion and the presence of circumstellar disks (Natta et al (2004), Apai et al (2005), Luhman et al (2007)). Thus they will drive jets and HH flows as well (Masciadri and Raga 2004). Searches for HHOs from very low-mass stars and BDs are being undertaken (e.g. Fernández and Comerón (2005), Wang and Henning (2006)), and the detection of jets from BDs were reported (Whelan et al (2005), Whelan et al (2007)). While these objects are relatively evolved (Class II), our unbiased search for HHOs associated with dark clouds and globules aims at revealing sources which are even younger (Class I). In the following we present three examples of young low-mass objects, for which our investigation yielded new insights and led to a revision of the current knowledge.

2 Target Selection and Observational Technique

The results presented here result from a general search for candidate HHOs using archival data and observations performed with the 2-m telescope of the Thüringer Landessternwarte Tautenburg (TLS). The archival work is based on DSS-II images and utilises the fact that the R filter almost peaks at $H\alpha$ and the $[S\ II]\ \lambda\lambda\ 6717, 6731$ emission lines. Thus, potential HHOs can be identified in an RGB image based on blue, red, and infrared DSS-II plates since their colours are very different from those of stars. So far the catalogs of Lee and Myers (1999) ([LM99]), Dutra and Bica (2002), and Dobashi et al (2005) were scrutinised for candidates. Since these can be mimicked e.g. by plate artifacts and minor planets, follow-up confirmation is necessary. For this purpose, northern candidates are checked against the R plate of DSS-I which is deep enough for the brighter ones while for southern objects,

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the SuperCOSMOS $H\alpha$ survey (Parker et al 2005) is being used. The TLS-CCD observations aim at the verification of suspected northern HHOs and a more detailed study. The $2k \times 2k$ prime focus CCD camera is used in the Schmidt configuration (diameter of the corrector plate 1.34 m) for $H\alpha$ and [SII] imaging. It provides a field of view (FOV) of $42' \times 42'$ at the pixel scale of $1''/235$. Long-slit spectroscopy of the candidate HHOs is obtained using the Nasmyth spectrograph which is equipped with a 2800×800 pixel SITe CCD. A slit width of $1''$ is normally used which, together with the V100 grism, leads to a resolution of $R \approx 2100$. Radial velocities and excitation conditions are derived from the spectra (see Stecklum et al (2004) for a more detailed description).

2.1 GF9-2 – The Pre-stellar Core revisited

GF9-2 is a millimetre source (Mezger 1994) in the globular filament #9 (Schneider and Elmegreen (1979); LDN 1082) associated with IRAS20503+6006. It was classified by Wiesemeyer et al (1999) as an extremely young source, probably in transition from Class –I to 0 (according to the classification scheme for young stellar objects of Adams et al (1987) and its extension to Class 0 by Andre et al (1993)). If true, GF9-2 would represent a rare case of an object turning from the pre-stellar to the proto-stellar phase. Also Furuya et al (2006) considered it to be in a very early stage of low-mass star formation because of the non-detection of a molecular outflow. Our search led to the discovery of 14 HHOs in the GF9 region which seem to belong to at least three HH flows. Five HHOs and the millimetre source GF9-2 are very well linearly aligned (correlation coefficient 0.9994, Fig. 1). Thus we conclude that they constitute a HH flow driven by IRAS20503+6006. Its overall length amounts to $43'.5$ which corresponds to 2.5 pc for an assumed distance of 200 pc. The outer HHOs have almost identical distances from the central source, suggesting a common origin from a past ejection event. Both southwestern components have the morphology of a reversed shock. Remarkably, the position angle of the flow of 28° is close to that of the projected B field ($\approx 20^\circ$) derived from ISO polarisation measurements (Clemens et al 1999), suggesting a collapse along the field lines. The radial velocity of $v_{\text{LSR}} = -69 \pm 5 \text{ km s}^{-1}$ of the innermost HHO (Fig. 1 insert) indicates that the north-eastern part of the flow is preceding. If the symmetry of the ejection also holds for this HHO, its distance from the driving source indicates that the receding counterpart is still hidden behind the dark cloud. The flow inclination derived from the radial velocity and the proper motion estimate amounts to $\approx 60^\circ$. The presence of a

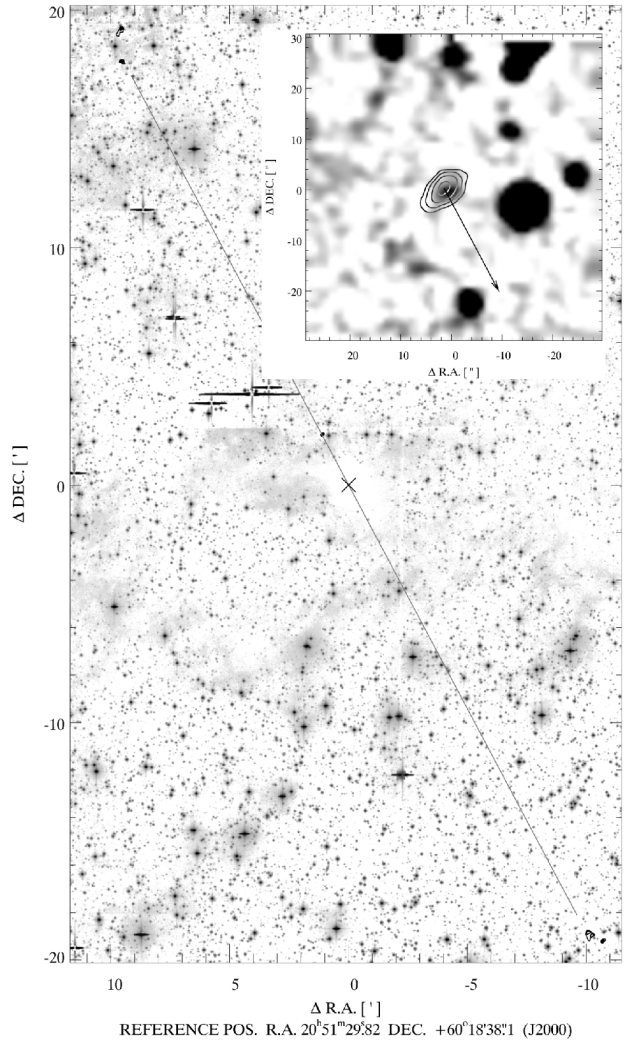


Fig. 1.— HH flow from GF9-2. The CCD-R-band image is shown together with contours of the continuum-subtracted $H\alpha$ emission. The position of the driving source embedded in GF9-2 is indicated by the inclined cross which corresponds to the location of the 3 mm source of Dobashi et al (2005). The grey line marks the flow axis, with the outermost HHOs next to its end points. The insert shows the DSS-II R image together with continuum-subtracted CCD- $H\alpha$ contours (levels $[3, 6, 12, 24]\sigma$) of the innermost HHO. The arrow points back to GF9-2. The proper motion within ≈ 12 yrs is evident and directed away from the source.

well developed, parsec-scale outflow from GF9-2, which escaped detection in molecular lines so far, indicates a more advanced evolutionary stage of this source than previously believed.

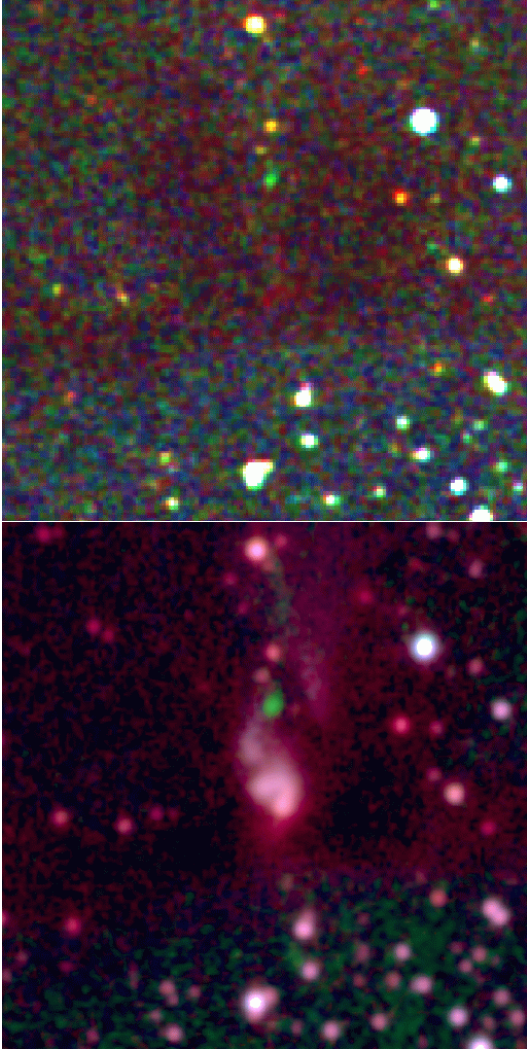


Fig. 2.— Top: DSS-II RGB image of a sub-region of LDN1415 (FOV $1'5 \times 1'5$). HH892 appears as green spot. Bottom: I, H α , and R colour composite based on TLS-CCD images.

2.2 L1415-IRS - The least luminous FUor/EXor

Our CCD observations confirmed the HH nature of a candidate object in LDN1415 (Fig. 2) which is now known as HH 892 (Stecklum et al 2007). Moreover, a new arcuate nebula associated with IRAS04376+5413 was found with an integrated *I*-band magnitude of 15.3 ± 0.1 mag. The comparison with archival data revealed that it brightened in *I* by 3.8 mag in recent years. The 2MASS images show a red non-stellar counterpart of the IRAS source, designated as L1415-IRS. The optical spectrum of the nebula displays a pronounced P-Cygni profile across the H α line. These findings represent clear evidence for an FUor- or EXor-type outburst

of the embedded object due to temporarily enhanced accretion. The brightening of the nebula results from the enhanced accretion luminosity of the young source and the diminished optical depth due to dust blow-out by the strong neutral wind. The luminosity of L1415-IRS during the inactive state integrated from $0.9 \mu\text{m}$ to $60 \mu\text{m}$ amounts to $0.13 L_{\odot}$ for the assumed distance of 170 pc. It is comparable to that of the low-luminosity source L1014-IRS (Young et al 2004), a possible substellar young object. L1415-IRS is by far the least luminous member of the sparse sample of FUors and EXors. Our monitoring shows that it has been in the active state for more than one year now with very minor changes in brightness. Thus, it seems likely that it is of FUor-type rather than being an EXor, as suggested in the more detailed paper by (Stecklum et al 2007). This finding challenges models of the FUor phenomenon based on opacity changes in the disk because of the low effective temperature of the central source. An alternative explanation is accretion bursts due to the capture of protoplanetary bodies was put forward recently by Vorobyov and Basu (2006).

2.3 BHR111 – A starless Core remains starless?

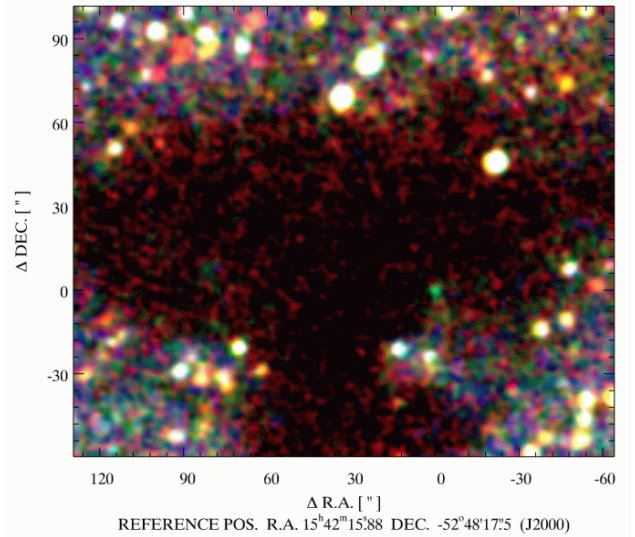


Fig. 3.— DSS-II RGB image of BHR111. The HHO is located at the reference position.

Within our DSS-II survey a very compact candidate HHO was spotted against the starless core [LM99]135, also known as BHR111 (Fig. 3). The object was detected on the corresponding SuperCosmos H α image which proves its reality. BHR111 is a rather isolated dark cloud. Two IRAS point sources within $7'5$ radius are planetary nebula. Thus, we conclude that the

HHO points to the presence of a young object within the cloud core which drives an outflow. This is the first case for the detection of an embedded source in a starless core by the identification of an associated HHO. The high stellar density of the surrounding field and the almost complete lack of foreground stars provide compelling evidence that the cloud is nearby. A value of 200 pc is adopted in the following. The cloud was observed with the *Spitzer* infrared space telescope, and the corresponding IRAC and MIPS data were retrieved from the archive. The MIPS 24 μm image shows three sources next to the core but only the one closest to the HHO is clearly detected at 70 μm . Thus we conclude that this object, BHR111-IR, is likely driving the outflow. The detection of a bipolar reflection nebula associated with the *Spitzer* source by deep high-resolution near-infrared imaging would rule out that it is a background object. The photometry derived from the *Spitzer* images yielded a spectral energy distribution (Fig. 4) which resembles that of L1014-IRS, suggesting a similar evolutionary phase. However, the infrared luminosity of $0.01 L_{\odot}$ of BHR111-IR is much weaker compared to L1014-IRS ($0.09 L_{\odot}$) which points to a less massive central source.

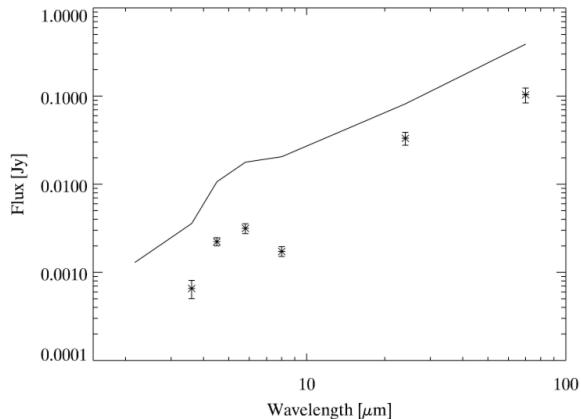


Fig. 4.— SED of the candidate proto-brown dwarf (Stecklum et al, in prep.). The line displays the SED of L1014-IRS (Young et al 2004) for comparison.

While it seems probable that L1014-IRS and L1415-IRS will eventually become very low-mass stars since their accretion still continues, BHR111-IRS may stay below the borderline separating BDs from stars indeed despite its ongoing mass assembly. If so the starless core would remain starless (at least for some time).

3 Outflows from Protoplanets

The increasing body of evidence for jet and outflow activity of young very-low mass stars and BDs shows that at least a substantial fraction of brown dwarfs form via disk accretion. This raises the question on the minimum mass of a young accreting object that will drive an outflow. The lower mass limit is probably governed by the condition to generate a magnetic field for the acceleration and collimation. Theoretical considerations suggest that a proto-Jovian body in a circumstellar disk might drive an outflow as well (Quillen and Trilling (1998), Fendt (2003)). However, proto-planetary flows will differ from those of the parent stars because of both the lower mass-loss rate and the orbital motion. The model of Fendt (2003) implies an $H\alpha$ luminosity of $L_{H\alpha} \approx 5 \times 10^{-6} L_{\odot}$ for an outflow emerging into a neutral environment ($L_{H\alpha}$ will be higher by an order of magnitude for a photoionised jet). However, Fendt (2003) notes that a stellar outflow which expands at its base will disrupt the proto-planetary flow. Therefore, proto-planetary jets can only be observed when the stellar accretion has ceased and planet formation is still ongoing. There might be a time window of a few million years after the clearance of the inner disk when proto-planetary jets can be observable. Extremely large telescopes are required to search for emission lines arising from the biconical surface caused by orbiting proto-planetary jets.

The Digitized Sky Survey was produced at the Space Telescope Science Institute under U.S. Government grant NAG W-2166. The images of these surveys are based on photographic data obtained using the Oschin Schmidt Telescope on Palomar Mountain and the UK Schmidt Telescope. The plates were processed into the present compressed digital form with the permission of these institutions. Based on observations performed at the Thüringer Landessternwarte Tautenburg. This research has made use of NASA's Astrophysics Data System Bibliographic Services and the SIMBAD database, operated at CDS, Strasbourg, France.

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